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EUREKA 147: Tests of the error performance of the DAB system

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Summary

This Report describes tests carried out by the BBC and other members of Eureka 147 Working Group 2-A, to assess the performance of the DAB (Digital Audio Broadcasting) system with a low carrier-to-noise ratio at the receiver. The tests were conducted using a number of listeners to judge the audio quality, making collaborative decisions with the knowledge of the conditions under which the system was operating at all times.

The primary purpose of the work described in this Report was to inform the Eureka 147 project about the failure characteristics of the DAB system as the carrier-to-noise ratio is reduced. Knowledge of the failure characteristics is important, because it enables broadcasters to monitor system performance at a time when services are being planned and when receiver techniques are developing. It should also enable the performance of the Eureka system to be compared with that of other systems.

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1. INTRODUCTION

The EBU and the Eureka 147 DAB (Digital Audio Broadcasting) project set up a joint group in 1992, in order to evaluate the performance of the Eureka 147 DAB system. One problem faced by the group was the planning of listening tests to determine the audible impairment of the DAB system at carrier-to-noise ratios approaching the failure point; a number of problems then became apparent and there were several reasons for this:

- Formal 'blind' subjective tests would require very many presentations of different conditions to each listener. These would be necessary if sufficient results were to be obtained for providing meaningful graphical data from a number of different types of channel. These channels would use various bit rates and channel code rates, under conditions where the received signal was being affected by Gaussian noise or subject to Rayleigh fading.
- With Rayleigh fading, the normal short test sequences would not be appropriate at the higher carrier-to-noise ratios; because, under these conditions, signal impairment results from short bursts of errors or muting which would be distributed over relatively long periods of time.
- Even if formal 'blind' subjective testing were to take place at the present time, as receivers evolve and their performance improves, the need will arise to repeat the tests from time to time; so it would be advantageous to try a less time-consuming method of evaluation.

Many of the results obtained in formal subjective tests of error performance are of relatively little interest. Probably, the most useful indications of performance are obtained from the carrier-to-noise ratios at the onset of audible impairment and at the failure point of the system (i.e. the point where the muting is so frequent that the programme is no longer of interest to the listener, or where speech becomes unintelligible).

With the above considerations in mind, the EBU/ Eureka joint group formulated a proposal for a new approach for evaluating the error performance of the DAB system. A series of tests was then carried out, using the proposed method, and these are described in this Report.

2. DESCRIPTION OF THE TESTS

A group of audio engineers from Working group 2-A of the Eureka 147 project (the group originally concerned with the audio coding aspects of the DAB system) met to conduct the assessment. A laboratory DAB chain was used, with a radio-frequency (r.f.) path simulation, commencing at the audio coder and ending at the output of a Eureka 147 "third generation" receiver. The simulation was capable of presenting an r.f. signal with a wide range of carrier-to-noise ratios at the receiver input. A block schematic diagram of the test arrangement is shown in Fig. 1 *(overleaf)*. The r.f. conditions during the tests were monitored and adjusted by an engineer experienced in r.f. techniques*.

Prior to the evaluation, BBC engineers listened to a wide range of programme material reproduced by the receiver, at carrier-to-noise ratios which were sufficiently low for the effects of errors to be noticeable**. Items found to be particularly critical for error tests included: glockenspiel; instruments of the clarinet, flute and oboe families; an unaccompanied soprano; bagpipes; saxophone; trumpet, and triangle. Of these, the glockenspiel and clarinet were selected as the most critical. These critical items were used for the tests, together with male and female speech and an item of popular music by the Swedish group 'ABBA'. All of these items are recorded on the EBU SQAM Compact Disc [1] and details are given in the Appendix. Other sources of programme were included in the search for material, but the most critical items were all contained in the SQAM CD, and it was convenient to use the same CD as the source for the speech and popular music items. In each test, the programme items were repeated until the listeners had reached a decision. Significantly longer periods of listening were needed for the tests

* G.N. Englefield was responsible for the setting-up and operation of the r.f. equipment.

** A.K. McParland assisted with the selection of the programme material, and participated in the assessment of the DAB System.

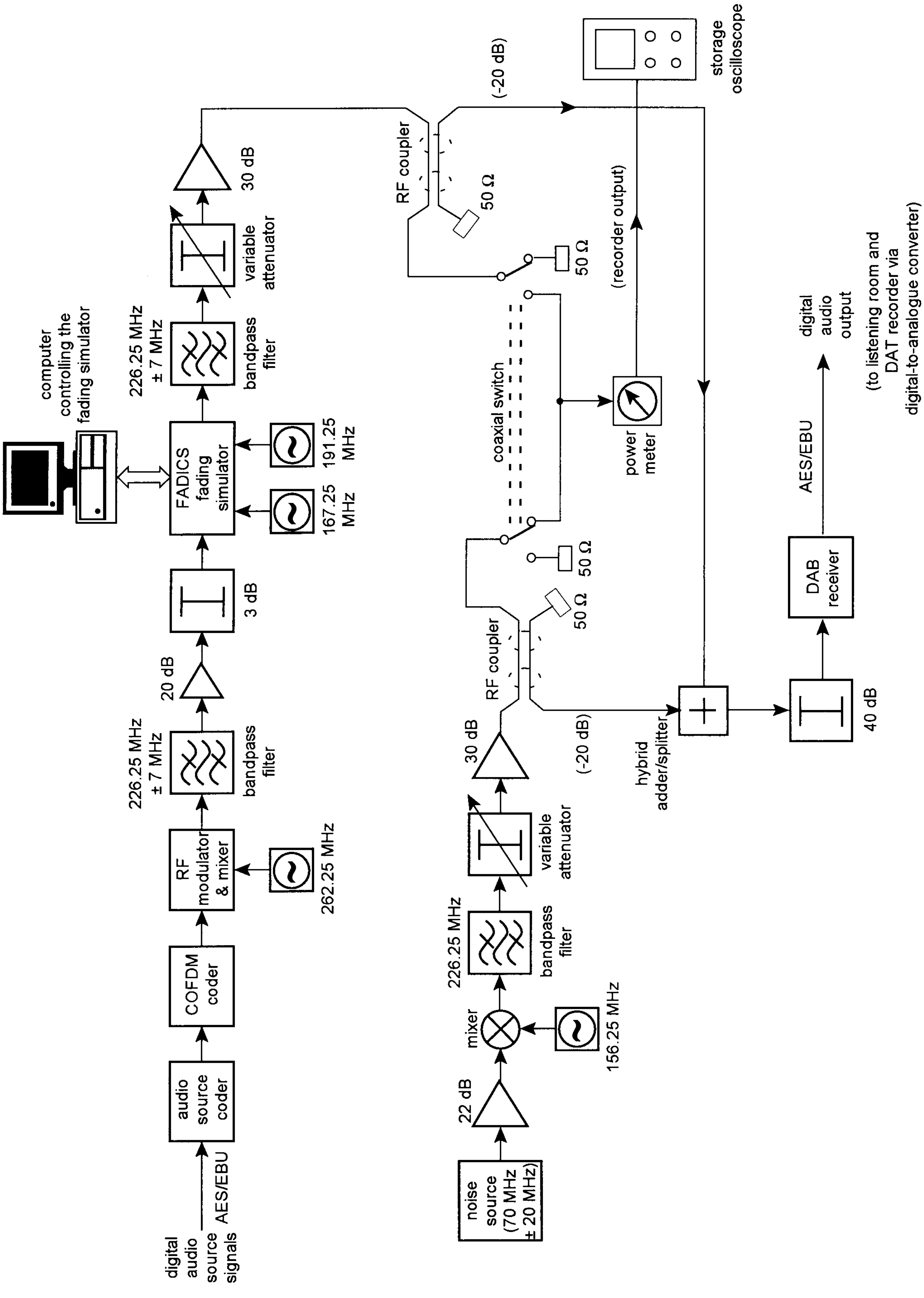

Fig. 1 - Block schematic diagram of the test arrangement.

involving a Rayleigh channel than for those involving a Gaussian channel, and the short programme items were repeated a number of times, over a period of several minutes.

The DAB system is able to carry bit-rate reduced digital audio signals at a number of different bit rates; coded as mono, stereo, joint stereo or dual channel [2]. The channel coding, based on punctured convolutional coding, affords protection against errors. The greatest protection is afforded at the lowest code rates, which have the highest proportions of redundant information. The audio bit rates and average code rates selected for testing were:

- 256 kbit/s stereo at a code rate of 0.57.
- 224 kbit/s stereo at a code rate of 0.60.
- 224 kbit/s stereo at a code rate of 0.50.
- 224 kbit/s joint stereo at a code rate of 0.50.
- 192 kbit/s joint stereo at a code rate of 0.51.
- 64 kbit/s mono at a code rate of 0.50.

Different transmission modes are used, depending on the system operating conditions. Two of the three modes, designated I and II, were selected for testing. Transmission mode I is intended for terrestrial Single Frequency Networks (SFN) and local-area broadcasting in Bands I, II and III. Transmission mode II is intended to be used for terrestrial local-area broadcasting in Bands I, II, III, IV, V and in the 1,452-1,492 MHz frequency band (i.e. L-Band).

The DAB signal comprises a succession of transmission frames of 96 ms duration in mode I and of 24 ms duration in mode II. Within these transmission frames, the synchronisation channel occupies approximately the first 2.544 ms in mode I, and approximately 0.636 ms in mode II [2].

In transmission mode I, the temporal guard interval of 246 µs permits the use of relatively widely-spaced transmitters, whereas in transmission mode II the guard interval is 62 µs, with a proportionally reduced transmitter separation. However, mode II has fewer radiated carriers; also, for mobile reception in L-Band, the greater frequency separation of the carriers is intended to reduce the effect of Doppler shifting for reception in moving vehicles, especially at the higher speeds. There are 1,536 radiated carriers in mode I, and 384 carriers in mode II, in a system bandwidth of about 1.54 MHz.

In the listening tests, the audio engineers asked for the carrier-to-noise ratio to be adjusted whilst they searched for two conditions, which were termed the 'onset of impairment' and the 'failure point' of the received DAB signal. The onset of impairment is important because it is the point at which the effects of errors start to become noticeable, and the failure point represents the point at which the listener would probably stop listening to the programme because it became unintelligible or because it no longer provided the enjoyment sought. The audio engineers defined these two points whilst listening to critical material prior to the start of the tests. The onset of impairment was defined as the point where 3 or 4 error-related events could be heard in a period of about 30 seconds. The failure point was defined as the point where the error-related events occurred virtually continuously, and muting took place 2 or 3 times in a period of about 30 seconds. When the appropriate condition had been reached, the r.f. engineer checked the carrier-to-noise ratio, and this was recorded by the audio engineers. The analogue audio signal at the output of the receiver was recorded on a DAT tape, before proceeding to the next test*.

The carrier-to-noise ratios, at the onset of impairment and at the failure point, were found in the manner described, using a Gaussian channel (with just Gaussian noise added to the received signal) and a channel with Rayleigh fading of the received signal (simulated using Grundig 'FADICS'** equipment [3]). The tests with a Gaussian channel represented the conditions in which a static receiver operates, and the FADICS was used to simulate two mobile reception conditions: one was reception in a vehicle moving at 15 km per hour (approximately 9.3 miles per hour) in an urban environment; the other was reception in a vehicle moving at 130 km per hour (approximately 81 miles per hour) in a rural environment. The mean carrier-to-noise ratio under Rayleigh fading conditions was estimated from a trace of the r.f. signal on a storage oscilloscope. The error in such a method of estimation is probably up to 2 dB.

Tests were conducted with simulated Rayleigh fading in the urban and rural conditions described above; transmission modes I and II were tested in Band III, and mode II alone in L-band. In some of the tests with Rayleigh fading, it was found impossible to obtain error-free reception, even at high carrier-to-noise ratios. Under these circumstances, the onset of

* The analogue output was recorded because a DAT recorder with a digital signal at its input might modify the signal in such a way that impairments are suppressed (e.g. by smoothing, during replay, timing disturbances which occur during recording), or added (e.g. when corruption of the signal causes a loss of frame alignment in the recorder).

** 'FADICS' stands for **FAD**ing **C**hannel **S**imulator.

errors could not be found; but, where possible, an approximate indication was obtained of the point at which the rate of occurrence of error-related events ceased to fall, as the carrier-to-noise ratio was increased from the failure point. This point was termed the 'transition point', because a transition occurred from an impairment condition which was dependent on a carrier-to-noise ratio, to a static condition where a steady residual (or 'background') error rate was evident.

It was recognised at the outset, that to test every combination of bit rate and channel code rate with each of the programme items, with both transmission modes, and with both Rayleigh fading and Gaussian noise, would be very time-consuming. The results presented in the first two tables, where Gaussian noise was added to the signal, were obtained using tests in which all of the selected programme items were used. In the subsequent tables, the results were obtained from tests using fewer programme items. However, in all cases the most critical item (clarinet) and the more critical speech item (female speech) were included. It will be evident, from the gaps in the tables, which bit rates and code rates were omitted from the tests with Rayleigh fading.

3. DISCUSSION OF RESULTS

A summary of the results of the listening tests is presented in Tables 1 to 8. Tables 1 and 2 give the results obtained with a Gaussian channel. Tables 3 and 4 give the results for simulated Rayleigh fading at VHF (226.25 MHz) in a rural environment, while Tables 5 and 6 *(see page 6)* give the results for simulated Rayleigh fading at VHF in an urban environment. Tables 7 and 8 *(see page 6)* give the results for simulated Rayleigh fading in the L-Band at 1,500 MHz, in rural and urban environments respectively, just for transmission mode II.

In any of the tests, it was difficult to be absolutely precise about either the failure point of the system or the onset of error-related impairment. In the former case, the carrier-to-noise ratio could not be set with sufficient precision to obtain exactly the defined failure characteristics, and there is typically an uncertainty of about 0.5 dB in the carrier-to-noise ratio at the failure point. When determining the onset of impairment (or the transition point, where there was a residual error rate even at high carrier-to-noise ratios), the less critical programme items tended to mask the error-related impairments to a significant degree, causing a greater spread of the carrier-to-noise ratios recorded for this condition. When examining the results in the tables, it should therefore be borne in mind that the higher carrier-to-noise ratios correspond to the performance of the system with critical programme material, and the lower carrier-to-noise ratios are for material which is not particularly critical. The uncertainty in determining the mean carrier-to-noise ratio for the tests with simulated Rayleigh fading (probably about 2 dB, as mentioned in the previous section of this Report) is a further factor to be borne in mind when examining the results in Tables 3 to 8 inclusive.

Looking first at the results for the DAB signal with a Gaussian channel, it is evident that the extra protection afforded to the signal by the lower channel code rate has a significant effect upon both the onset of impairment and the failure point. For both transmission modes, the onset of impairment occurs at carrier-to-noise ratios of between 7.0 dB and 9.0 dB, depending on the programme material, for a code rate of about 0.6, and occurs at carrier-to-noise ratios in the range 6.0 dB to 8.0 dB for a channel code rate of about 0.5. System failure occurs at carrier-to-noise ratios in the region of 5.5 dB to 6.0 dB at a code rate of about 0.6, and in the region of 4.5 dB to 5.0 dB for a code rate of about 0.5. So the DAB system operates consistently to a carrier-to-noise ratio about 1.0 dB lower with a code rate of 0.5, than with a code rate of 0.6. Typically, the onset of impairment occurs at a carrier-to-noise ratio 1.5 dB to 3.0 dB above the failure point. Mode I and mode II have the same failure points, and the onset of impairment occurs at the same carrier-to-noise ratios.

The effect of occasional deep carrier fades in all the tests with simulated Rayleigh fading is to make failure of the DAB signal occur at rather higher mean carrier-to-noise ratios than those measured at the failure point with a Gaussian channel. At VHF, in Band III, the better-protected signals with a channel code rate of about 0.5 failed at carrier-to-noise ratios in the region of 9.0 dB to 10.0 dB, whilst the less well-protected signals with a channel code rate of about 0.6 failed at carrier-to-noise ratios in the region of 11.0 dB to 12.0 dB. This is the case for both rural and urban fading models; the results are summarised in Tables 3 to 6. The better-protected DAB signals operate down to a carrier-to-noise ratio about 2.0 dB lower than the less well-protected signals.

With the rural fading model and transmission mode I, it was impossible to find the onset of impairment, because there were still error-related impairments at relatively high carrier-to-noise ratios; so the point at which the transition to the residual (or 'background') error rate occurred was found instead. This was the case, too, for mode II with the less well-protected signals, but the onset of impairment

Table 1: Transmission mode I, Gaussian noise added to received Band III signal. Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo	7.0/8.0	5.5
224 kbit/s, code rate 0.60 stereo	8.0/9.0	5.5/6.0
224 kbit/s, code rate 0.50 stereo	6.5/7.5	4.5/5.0
224 kbit/s, code rate 0.50 joint stereo	6.0/7.5	4.5
192 kbit/s, code rate 0.51 joint stereo	6.5/8.0	4.5/5.0
64 kbit/s, code rate 0.50 mono	6.0/7.5	4.5

Table 2: Transmission mode II, Gaussian noise added to received Band III signal. Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo	7.0/8.5	5.5/6.0
224 kbit/s, code rate 0.60 stereo	7.5/9.0	5.5/6.0
224 kbit/s, code rate 0.50 stereo	6.0/7.5	4.5/5.0
224 kbit/s, code rate 0.50 joint stereo	6.0/7.0	4.5
192 kbit/s, code rate 0.51 joint stereo	6.5/8.0	4.5/5.0
64 kbit/s, code rate 0.50 mono	6.5/7.5	4.5

Table 3: Transmission mode I, Band III signal subject to Rayleigh fading (rural). Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo		11.0/12.0
224 kbit/s, code rate 0.60 stereo	20.0*	12.0
224 kbit/s, code rate 0.50 stereo	16.0/18.0*	10.0
224 kbit/s, code rate 0.50 joint stereo		9.0/10.0
192 kbit/s, code rate 0.51 joint stereo	17.0*	9.0/10.0
64 kbit/s, code rate 0.50 mono		9.0

Table 4: Transmission mode II, Band III signal subject to Rayleigh fading (rural). Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo	19.0*	11.0/12.0
224 kbit/s, code rate 0.60 stereo	19.0/20.0*	12.0
224 kbit/s, code rate 0.50 stereo	16.0/18.0	9.5
224 kbit/s, code rate 0.50 joint stereo	16.0	10.0
192 kbit/s, code rate 0.51 joint stereo	17.0	9.0
64 kbit/s, code rate 0.50 mono	17.0	10.0

* The signal suffers from errors even at relatively high carrier-to-noise ratios. The C/N values marked with an asterisk are for the point where the transition occurs betweeen the 'background' error rate and an error rate which varies with changes in the C/N ratio.

Table 5: Transmission mode I, Band III signal subject to Rayleigh fading (urban). Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo		
224 kbit/s, code rate 0.60 stereo	17.0/19.0	11.0
224 kbit/s, code rate 0.50 stereo	15.0/17.0	9.0
224 kbit/s, code rate 0.50 joint stereo		
192 kbit/s, code rate 0.51 joint stereo		
64 kbit/s, code rate 0.50 mono		

Table 6: Transmission mode II, Band III signal subject to Rayleigh fading (urban) Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo		
224 kbit/s, code rate 0.60 stereo	17.0/19.0	11.0
224 kbit/s, code rate 0.50 stereo	13.0/17.0	9.0/10.0
224 kbit/s, code rate 0.50 joint stereo		
192 kbit/s, code rate 0.51 joint stereo		
64 kbit/s, code rate 0.50 mono		

Table 7: Transmission mode II, L-Band signal subject to Rayleigh fading (rural). Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo		
224 kbit/s, code rate 0.60 stereo	**	12.0
224 kbit/s, code rate 0.50 stereo	19.0/20.0*	10.0
224 kbit/s, code rate 0.50 joint stereo		
192 kbit/s, code rate 0.51 joint stereo		
64 kbit/s, code rate 0.50 mono		

Table 8: Transmission mode II, L-Band signal subject to Rayleigh fading (urban). Carrier-to-noise ratios at the onset of impairment and failure points.

Audio bit rate, code rate stereo/mono/joint stereo	C/N ratio, dB, at the onset of impairment	C/N ratio, dB, at the point of failure
256 kbit/s, code rate 0.57 stereo		
224 kbit/s, code rate 0.60 stereo	15.0/17.0	9.0
224 kbit/s, code rate 0.50 stereo	11.0/15.0	7.0
224 kbit/s, code rate 0.50 joint stereo		
192 kbit/s, code rate 0.51 joint stereo		
64 kbit/s, code rate 0.50 mono		

* The signal suffers from errors even at relatively high carrier-to-noise ratios. The C/N values marked with an asterisk are for the point where the transition occurs between the 'background' error rate and an error rate which varies with changes in the C/N ratio.

** Frequent error-related events were perceived, even at C/N ratios as high as 30 dB. It proved impossible to determine the onset of errors or a transition point.

could be determined in this mode with the better-protected signals. With the urban fading model, the onset of impairment could be determined in both modes. Most of the results indicated that the onset of impairment occurs in the region of 15.0 dB to 17.0 dB carrier-to-noise ratio for the better-protected signals, and 17.0 dB to 19.0 dB for the less well-protected signals. However, one or two results outside this region indicated that the onset of impairment might occur at carrier-to-noise ratios as low as 13.0 dB and as high as 20.0 dB under some circumstances.

The listeners had more difficulty in forming their judgements with the Rayleigh fading tests than with the tests using Gaussian noise, so it is probably fair to say that the spread in the results indicates greater uncertainty. There were slow variations in the carrier level, as well as rapid fades, and even longer periods of listening would probably have been justified before arriving at each assessment. It seems that the onset of impairment is typically 6.0 dB to 8.0 dB above the failure point.

There were error-related impairments at relatively high carrier-to-noise ratios in the simulated rural environment (see Tables 3 and 4). However, one should bear in mind that the Rayleigh model of rural fading is exceptionally severe. It can introduce fades over a wide range of frequencies, and this "flat" fading characteristic causes very severe reductions in signal strength which are only rarely encountered in practice.

Tables 7 and 8 present summaries of the results obtained when Rayleigh fading in the L-Band was simulated in the rural and urban environments, respectively. In the rural environment, the residual errors were very frequent, and not even a transition point could be found with any certainty with the less well-protected DAB signals. In the urban environment, the onset of impairment could be found. The system failed in the rural environment at carrier-to-noise ratios of about 10.0 dB and about 12.0 dB, for channel code rates of 0.5 and 0.6 respectively. In the urban environment, the system failed at carrier-to-noise ratios of about 7.0 dB and about 9.0 dB, for the same two code rates. Where the onset of impairment could be found, in the urban environment, it seemed to occur 4.0 dB to 8.0 dB above the system failure point.

4. CONCLUSIONS

Listening tests, involving a number of listeners making a collaborative decision, have been used to assess the error performance of the Eureka 147 DAB system. The listeners were aware of the conditions under which the system was operating, and directed adjustments to the carrier-to-noise ratio of the DAB signal at the input to the receiver, in order to find the onset of impairment and the failure point of the system. These were subjective tests, but in no sense 'blind' tests. They were, however, a much more expeditious way of obtaining an assessment of the DAB system's performance than 'blind' tests. It was not necessary to assess performance at so many different carrier-to-noise ratios as would have been needed for 'blind' tests; but fewer results were available at the conclusion of the tests, consequently there were not the same possibilities for statistical processing.

On adding Gaussian noise to the DAB signal, the failure point of signals with a channel code rate of about 0.6 occurs at a carrier-to-noise ratio of 5.5 to 6.0 dB, and for signals with a code rate of 0.5 at a carrier-to-noise ratio approximately 1 dB lower. Under simulated Rayleigh fading conditions, in Band III (VHF) the failure point for signals with a code rate of 0.6 is at a mean carrier-to-noise ratio of approximately11.0 to 12.0 dB, and for signals with a code rate of 0.5, at a carrier-to-noise ratio approximately 2 dB lower. In the L-Band, under simulated Rayleigh fading conditions, the failure points are at carrier-to- noise ratios of approximately 12.0 dB (rural) and 9.0 dB (urban) for a code rate of 0.6, and at carrier-to- noise ratios approximately 2 dB lower for a code rate of 0.5.

When it was possible to determine the onset of impairment for the DAB signal, this was typically 1.5 to 3.0 dB above the failure point when Gaussian noise was added to the DAB signal. It was typically 6.0 to 8.0 dB above the failure point of Rayleigh fading in Band III, and 4.0 to 8.0 dB above the failure point for a simulation of Rayleigh fading in an urban environment in the L-Band.

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APPENDIX

Details of the Recordings used in the Tests
EBU SQAM Compact Disc (track and index numbers in brackets)

1.	Clarinet tune	(16.2)
2.	Glockenspiel tune	(35.2)
3.	Female speech (English)	(49.1)
4.	Male speech (English)	(50.1)
5.	ABBA	(69.1)